Relativity with or without light and Maxwell

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Abstract. The complex relationship between Einstein's second postulate and the Maxwell electromagnetic theory is elucidated. A simple deduction of the main results of the Ignatowski approach to the theory of relativity is given. The peculiar status of the principle of relativity among the Maxwellians is illustrated.

1. Introduction

Recent papers published in pedagogical journals [1-9] testify that the problem of how to teach special relativity continues to be a fascinating topic, discussed at various levels of sophistication. This is no wonder because the concepts of where, when and why are essential for our existence as conscious beings, and with the theory of relativity our instinctive world view is at stake. It is a common experience of high school physics teachers that even the students with aversion to physics lose their apathy and listen with ears wide open when confronted with the theory of relativity .

The historical path to special relativity starts from the second postulate introduced by Einstein in 1905 [10]. Immediately after the publication of reference [10], he noted that the second postulate is contained in Maxwell's equations [11], suggesting thus the approach recently elaborated by Aguirregabiria *et al* ([1], [12]).

In the present paper, which was inspired by references [1-12], we venture to illuminate some obscure corners and to simplify some involved points in the relativistic arguments. We believe that the present attempt could save some time and effort to the teachers and students of special relativity at undergraduate level, and provides some fresh insights. In Section 2 we discuss the complex relationship between Maxwell's equations and the second postulate. Section 3 is an attempt to deduce the main results of the 'relativity without light' approach in a simple way. The concluding Section 4 contains a praise of the second postulate and a historical remark on the peculiar status of the principle of relativity among the Maxwellians in the late nineteenth century.

2. Maxwell's equations, 'inertia-time' and 'light-time'

Starting from the postulated validity of Maxwell's equations in any given inertial frame involves that the meaning of 'time' has already been settled in that frame, according to the standard definition based on Galileo's principle of inertia ('inertia-time'). As is well known, inertia-time and the validity of Maxwell's equations in any one inertial frame S imply that one can also introduce 'light-time' in that frame, based on rectilinear propagation of electromagnetic waves† in vacuum at the same speed $c \equiv (\epsilon_0\mu_0)^{-1/2}$ in all directions; light-time is identical with inertia-time in S. Applying now the principle of relativity (assuming also that ϵ_0 and μ_0 are frame-independent), it follows that one should look for coordinate transformations between two inertial frames S and S', in uniform motion with respect to one another, that are consistent with light-time. (Inertia-time and light-time are identical in any frame, and inertia-time puts no constraints on the transformations sought, except that the validity of Galileo's principle of inertia in S should imply its validity in S'.) Clearly, the transformations cannot be of the Galilean type, involving $t' = t$, since such transformations destroy invariance of c.‡ Assumed uniformity of space and time implies that the transformations must be linear; employing also invariance of the speed of light c and assuming isotropy of space, one obtains the Lorentz transformations.§

The above argument seems to be condensed in the footnote from Einstein's second relativity paper: "The principle of the constancy of the velocity of light used there [in [10]] is of course contained in Maxwell's equations." [11] The laconic footnote probably reveals Einstein's *original* train of thought leading him to special relativity: from Maxwell's equations to the constancy of the speed of light, and through the principle of relativity and properties of space and time, to the Lorentz transformations.

† Following Maxwell (1864), "light itself [...] is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws." [13]

‡ The fact that 'now' is not the same for all inertial observers is a miracle of different kind than the one that the motion of the moon about the earth and the falling of an apple have a common root. (Newton proved the latter in the third book of *Principia*.) According to Newton, "relative, apparent and common time is any sensible and external measure (whether accurate or unequable) of duration by means of motion;" "duration or the perseverance of the existence of things" is Newton's synonym for his "absolute, true and mathematical time." Einstein's postulated uniform propagation of light in vacuum, an ideal time–keeper (Silberstein's term) identical for all inertial observers and inaccessible to experimental verification, appears to be a perfect *analogon* of Newton's absolute time which "of itself and of its own nature, without relation to anything external, flows equably," and the parts of which "make no impressions on the senses" ("*non incurrunt in sensus*;" all quotations of Newton are from the first *Scholium* of *Principia* [14]). Newton, and all physicists before Einstein (including Voigt, Larmor, Lorentz and Poincaré [15-18]), took it for granted that there was only one 'time,' absolute Newtonian time, for all observers in motion with respect to one another. Einstein was bold enough to venture that each inertial observer has her/his own *absolute Einsteinian time*.

§ Einstein's original derivation of the Lorentz transformations [10], while cumbersome, is perfectly correct, without involving *Galilean transformations*, as clarified by Martinez [19]. Einstein for the first time gave the explanation of how uniformity of space and time implies the linearity of the transformations in [20], Section 7.4; in the same paper he gave for the first time a definition of a clock ([20], p 21).

However, in 1905 instead of starting from Maxwell's equations Einstein chose a different path [10]. Why? He gave an explanation thirty years later, at the beginning of his penultimate published attempt to derive the mass–energy relation: "The special theory of relativity grew out of the Maxwell electromagnetic equations. So it came about that even in the derivation of the mechanical concepts and their relations the consideration of those of the electromagnetic field has played an essential role. The question as to the independence of those relations is a natural one because the Lorentz transformation, the real basis of the special relativity theory, in itself has nothing to do with the Maxwell theory and because we do not know the extent to which the energy concepts of the Maxwell theory can be maintained in the face of the data of molecular physics." [21]

However, as noted in [22], Einstein in 1905 would have had to derive the Lorentz transformations following the template of thermodynamics, making them independent of the Maxwell theory, even if he were quite ignorant of light quanta or Planck's 1900 derivation of the black–body radiation formula. A definition of time that is as simple as possible must conceptually precede any discussion about "the laws according to which the states of physical systems change," including the domain of the validity of Maxwell's equations. Attempting to keep the Lorentz transformations divorced from the Maxwell electromagnetic theory, Einstein took a necessary condition of the Maxwell theory to be his principle of the constancy of the speed of light (the notorious "second postulate"). This principle, which appears to be 'simplicity itself,' combined with the (meta-)principle of relativity, is the crux of special relativity. Einstein's 'definite velocity V' of propagation of light in vacuum (he used the symbol 'V' instead of 'c' in [10]), appearing in the introduction and in paragraph 2 of [10], does not have the familiar meaning of a derived quantity, $V =$ (light path)/time interval, where 'time interval' is a segment of inertia–time. Instead, Einstein's V is a primitive quantity (of course, all other speeds are derived quantities), and 'time interval' is *by definition* equal to (one–way light path)/V. Thus the speed of light in vacuum is by definition equal to the universal constant V, identical for all inertial observers, in perfect disagreement with our instinctive Galilean mentality.‖ Two circumstances were decisive for Einstein's argument: first, Maxwell's equations can be simply made Lorentz–covariant and thus consistent with the principle of relativity by appropriately defining the transformations for the electric and magnetic fields and charge and current densities (the fact already known (partly) to Lorentz [25] and (fully) to Poincaré [26], but also (partly) to Larmor [27], cf [16]), and, second, empirical evidence for Maxwell's theory in pseudo–inertial

‖ As is recalled in [23], Einstein's second postulate has a rather intricate content. "It postulates that, relative to any given inertial frame, the one-clock two-way speed of light in vacuum V (a measurable physical quantity and, as measurements reveal, a universal constant) is constant and independent of the velocity of light source and equals the one-way two-clock speed of light in vacuum (an immeasurable quantity). [...] It should be pointed out that throughout the Relativity Paper Einstein used the same symbol ('V') for the speed of light in vacuum and the phase velocity of electromagnetic waves in vacuum according to the 'Maxwell-Hertz equations', linking thus special relativity with Maxwell's theory, and at the same time linking the new time keeper (propagation of light) with the earlier ones (cf [24])."

frame tied to the earth.

The above discussion reveals that Einstein's second postulate conceptually precedes the principle of relativity. The rich content of the second postulate is understated in the laconic Einstein's footnote [11] quoted above.

3. Relativity without the light postulate

The traditional way of deriving the Lorentz transformations, starting from Einstein [10], is *basically* based on the following assumptions:

1. There is a frame of reference in which spatial coordinates x, y and z are Cartesian coordinates (Euclidean geometry applies), and time coordinate t is defined through 'light–time' (Einstein's second postulate applies so the one–way two–clock speed of light is by definition the known constant, $c \equiv (\epsilon_0\mu_0)^{-1/2}$); we will call a frame of reference with such properties of space and time the 'primitive frame.'

2. Each observer in uniform motion with respect to the primitive frame ('primitive observer') has her/his own primitive frame so the speed of light is the universal constant, c, the same for all primitive observers.

3. The principle of relativity applies to primitive frames.

4. Uniformity of space and time and isotropy of space.

The above assumptions are sufficient for deriving the Lorentz transformations. Since light–time is consistent with inertia–time, by adding Galileo's principle of inertia each primitive frame is also inertial frame, but Galileo's principle is not necessary for deriving the Lorentz transformations.

One may ask at which coordinate transformations one arrives with the principle of relativity but without light and the second postulate, replacing in the above assumptions primitive frame with inertial frame, employing inertia–time based on Galileo's principle of inertia. As is well known, we owe the query and the correct answer to it to Vladimir Ignatowski [28]. In what follows we give a simple derivation of Ignatowski's main results.

Consider two inertial frames S and S' in the standard configuration (S' is in uniform motion with respect to S along the common positive $x - x'$ axes at speed v, $y-$ and $z-$axis parallel to the $y'-$ and $z'-$axis, respectively, the origins coincide at $t = t' = 0$), Uniformity of space and time implies that required coordinate transformations must be linear; also, isotropy of space implies that x' is independent of y and z. Consequently,

$$x' = x/F_v + t/G_v \,, \tag{1}$$

where F_v and G_v are parameters dependent solely on v, as yet unknown. Setting for simplicity $y' = y$ and $z' = z$, our considerations will be restricted to x and t only. Employing the principle of relativity, *assuming* velocity reciprocity¶, one has

$$x = x'/F_{-v} + t'/G_{-v} \tag{2}$$

¶ Velocity reciprocity means that the velocity of the S' frame with respect to the S frame is the opposite of the velocity of S with respect to S'. Many an author, including Ignatowski [28], takes velocity reciprocity as an immediate and self-evident consequence only of the principle of relativity. However, various additional assumptions are also required, such as uniformity of space and of time, Considering trajectories of the origins and lengths of moving unit rods, one obtains

$$1/G_v = -v/F_v\,, \quad 1/G_{-v} = v/F_{-v}\,, \quad F_v = F_{-v}\,. \tag{3}$$

Eqs. (1)-(3) give [33]

$$x' = \frac{x - vt}{F_v}\,, \quad \text{and} \quad t' = \frac{t - \kappa_v x}{F_v}\,, \tag{4}$$

where

$$\kappa_v \equiv \frac{1 - F_v^2}{v}\,. \tag{5}$$

It is convenient to write eqs. (4) in matrix form [34,35]

$$\begin{pmatrix} t' \\ x' \end{pmatrix} = \frac{1}{F_v} \begin{pmatrix} 1 & -\kappa_v \\ -v & 1 \end{pmatrix} \begin{pmatrix} t \\ x \end{pmatrix} \equiv \Lambda_v \begin{pmatrix} t \\ x \end{pmatrix} \tag{6}$$

Introduce now a third inertial frame S'', in the standard configuration with S', moving at the speed u relative to S'. One has

$$\begin{pmatrix} t'' \\ x'' \end{pmatrix} = \frac{1}{F_u} \begin{pmatrix} 1 & -\kappa_u \\ -u & 1 \end{pmatrix} \begin{pmatrix} t' \\ x' \end{pmatrix} \equiv \Lambda_u \begin{pmatrix} t' \\ x' \end{pmatrix} \tag{7}$$

where $\kappa_u \equiv (1 - F_u^2)/u$. Eqs. (6) and (7) obviously give

$$\begin{pmatrix} t'' \\ x'' \end{pmatrix} = \frac{1}{F_u F_v} \begin{pmatrix} 1 + \kappa_u v & -\kappa_u - \kappa_v \\ -u - v & 1 + \kappa_v u \end{pmatrix} \begin{pmatrix} t \\ x \end{pmatrix} \equiv \Lambda_u \Lambda_v \begin{pmatrix} t \\ x \end{pmatrix} \tag{8}$$

It is natural to require that coordinate transformations between two inertial frames satisfy closure property, i.e. the successive application of two such transformations yields a third such transformation of the same form and content. Comparing eqs. (8) and (6), the requirement can be satisfied if and only if

$$\kappa_u v = \kappa_v u\,, \tag{9}$$

and

$$1 + \kappa_u v \neq 0\,. \tag{10}$$

spatial and temporal isotropy, and causality, as pointed out by Berzi and Gorini [29] and by Lévy-Leblond [30]; a thorough discussion of the issue was recently published by Patrick Moylan [5].

By the way, Einstein's first derivation of the Lorentz transformations (given in paragraph 3 of [10]) based on the postulated, finite and known, universal speed V (Einstein's symbol for 'c'), does not assume velocity reciprocity, but deduces it. It is perhaps amusing to note that therein he denotes by $\varphi(v)$ both his a and $a\beta$, where $\beta \equiv \frac{1}{\sqrt{1-(v/V)^2}}$. Moreover, he employs three reference frames (which he calls 'coordinate systems'), 'resting frame' K with coordinates x, y, z and t, 'moving frame' k with coordinates ξ, η, ζ and τ, and a third frame K' with coordinates x', y', z' and t', moving relative to k. In the same paragraph 3 of [10] he uses the symbol x' also for $x - vt$, so x', y, z and t refer to *coordinate systems* introduced in the *reference frame* K. All that of course does not add to lucidity; reading Einstein, like reading Maxwell, is always an adventure *par excellence* [31,32].

Condition (9) is tantamount to

$$\frac{\kappa_u}{u} = \frac{\kappa_v}{v} \equiv \Omega\,. \tag{11}$$

Since u and v are arbitrary, Ω must be a universal constant, the same for all inertial observers. Conditions (10) and (11) give

$$1 + \Omega uv \neq 0\,, \tag{12}$$

which excludes the possibility of negative Ω (otherwise, one would have $1+\Omega uv = 0$ for $uv = 1/|\Omega|$). Thus the universal constant Ω must be nonnegative,

$$\Omega \geq 0\,. \tag{13}$$

Expressed in terms of Ω, employing condition (12), matrices Λ_v and $\Lambda_u\Lambda_v$ become

$$\Lambda_v \equiv \frac{1}{F_v}\begin{pmatrix} 1 & -v\Omega \\ -v & 1 \end{pmatrix}, \tag{14}$$

$$\Lambda_u\Lambda_v \equiv \frac{1}{F_w}\begin{pmatrix} 1 & -w\Omega \\ -w & 1 \end{pmatrix}, \tag{15}$$

where

$$w \equiv \frac{v+u}{1+\Omega vu}\,, \tag{16}$$

and

$$\frac{1}{F_w} \equiv \frac{1+\Omega uv}{F_u F_v}\,. \tag{17}$$

Equations (5) and (11) imply

$$F_v = \sqrt{1-\Omega v^2}\,, \tag{18}$$

since only the positive value of F_v makes sense. Thus also $F_u = \sqrt{1-\Omega u^2}$, and F_w from eq. (17) must be equal to $\sqrt{1-\Omega w^2}$ with w given by eq. (16). One can verify that this is indeed so and consequently w is the speed of the frame S'' with respect to the S frame.

There are two possible choices for Ω, zero or a positive value. $\Omega = 0$ yields the Galilean transformations

$$x' = x - vt\,, \quad y' = y\,, \quad z' = z\,, \quad t' = t\,, \tag{19}$$

which imply that there is one time for all inertial observers (identical with Newton's absolute time), that a standard of length always has the same length independent of its velocity, and that v can be arbitrarily large. While in perfect agreement with our instinctive Galilean mentality, the Galilean transformations cannot be made compatible with a consistent interpretation of experience.[+]

The choice $\Omega > 0$ yields the well-known Ignatowski transformations [28]

$$x' = \frac{1}{\sqrt{1-\Omega v^2}}(x - vt)\,, \quad y' = y\,, \quad z' = z\,, \quad t' = \frac{1}{\sqrt{1-\Omega v^2}}(t - \Omega v x)\,. \tag{20}$$

Putting

$$\overline{c} \equiv \frac{1}{\sqrt{\Omega}}\,, \tag{21}$$

and employing eq. (18), one obtains that

$$v < \overline{c}\,. \tag{22}$$

Thus $\overline{c}$ is the universal *limit* speed for massive particles (a supremum of possible particle speeds), as yet unknown, for the case $\Omega > 0$. Putting also

$$\gamma_v \equiv \frac{1}{\sqrt{1 - v^2/\overline{c}^2}}\,. \tag{23}$$

eqs. (20), (16) and (17) become

$$x' = \gamma_v(x - vt)\,, \quad y' = y\,, \quad z' = z\,, \quad t' = \gamma_v(t - vx/\overline{c}^2)\,, \tag{24}$$

$$w \equiv \frac{v + u}{1 + vu/\overline{c}^2}\,, \tag{25}$$

$$\gamma_w \equiv \gamma_u \gamma_v (1 + vu/\overline{c}^2)\,. \tag{26}$$

Since we concluded above that w is the speed of S'' relative to S, in eq. (25) one recognizes the familiar relativistic composition of velocities, and in eq. (26) the familiar relativistic transformation for gamma factors (cf, e. g., [37, 38]).

Thus the Ignatowski transformations (20) are Lorentz–like transformations. To obtain the Lorentz transformations, i.e. to ascertain the value of the universal constant $\overline{c}$, one must turn to phenomena, without invoking properties of light or Maxwell's electromagnetic theory.

[+] Newton's absolute space (that "by its own nature without relation to any thing external remains always uniform and unchangeable") and absolute time (that "by its own nature without relation to any thing external flows equably") appear to be the natural habitat for the Galilean transformations. As the parts of absolute space "do by no means come under the observation of our senses" ("*non incurrunt in sensus*"), and the same applies to absolute time, it appears that those *absolute* concepts remain transcendental and thus perhaps fruitless (compare Maxwell's poetic discussion in his *Matter and Motion* [36]; by the way, what Maxwell calls "the doctrine of relativity of all physical phenomena" is the root of Poincaré–Einstein's principle of relativity). But, keeping in mind that "everything which is not forbidden is allowed," one should not dispense with a possible interpretation of the Galilean transformations.

4. Concluding comments

Turning to phenomena, however, is tricky considering that inertial observers inhabit "ideal infinitely extended gravity-free inertial frames," whereas in the real world their habitat is restricted to "the freely falling nonrotating local frames" [37].* We quoted above Einstein's clear-cut statement that "the Lorentz transformation, the real basis of the special relativity theory, in itself has nothing to do with the Maxwell theory [...]," which is widely endorsed in the literature. ("Special relativity would exist even if light and electromagnetism were somehow eliminated from nature."[37]) While various scenarios that have been proposed to ascertain the value of $\bar{c}$, without invoking properties of light or Maxwell's electromagnetic theory, appear to be free from logical errors (cf, e. g., [6, 33, 40]), none of them can be actually implemented.

On the other hand, Einstein's second postulate combined with the principle of relativity states, basically: first, there is a universal finite speed, c, the same for all *primitive observers*, and light propagates in vacuum at the universal speed; second, the universal speed c is a primitive quantity, and 'time' ('light–time', 'duration') in any primitive frame is a derived quantity through time interval $\stackrel{\mathrm{d}}{=}$ light path/c; third, the magnitude of c is equal to the speed of propagation of electromagnetic waves in vacuum, $(\epsilon_0\mu_0)^{-1/2}$ as given by Maxwell's electromagnetic theory, and also it is equal to the one-clock two-way speed of light as ascertained by terrestrial measurements and consistent with astronomical observations.

Thus, whereas in 'relativity without light and electromagnetism' $\bar{c}$ is the universal limit speed determinable only in principle through Gedankenexperiments, in the second postulate approach c is the speed which pertains to a real phenomenon (the essential one for our experience of the world), "concerning which we know something certain [...] in a higher degree than for any other process which could be considered, thanks to the investigations of Maxwell and H. A. Lorentz" [41].♯ The second postulate combined with the principle of relativity, while counterintuitive, gives a simple path to the concepts of time and primitive frame, and to the Lorentz transformations. The second postulate is more fundamental than the principle of relativity because a definition of time that is as simple as possible must conceptually precede any discussion about "the laws under which the states of physical systems undergo changes."

Is it indeed a surprise that one can deduce the Lorentz–like transformations from the principle of relativity and Galileo's principle of inertia, assuming uniformity of space and time, spatial and temporal isotropy, and causality, without postulating a universal finite speed, as Einstein did? With hindsight, *post festum ex post facto*, it appears that

* This fact was *basically* well known to Newton, see corollaries V and VI of the Laws of Motion [14] and also [39].

♯ It should be stressed that relativistic length contraction and clock retardation cannot be verified directly. As Jefimenko [42] notes, Einstein's method for measuring the length of a moving rod proposed in [10], "was, of course, merely a 'Gedankenexperiment,' that is, an imaginary procedure, a verbalization of [equation $x' = \gamma(x - vt)$], that cannot be actually implemented."

the Ignatowski's result could have been anticipated by the following simple argument. If there is the universal (signal) speed that is infinite, then $t' = t$, according to clock synchronization. Applying *modus tollens*, if $t' \neq t$, then either the universal speed is finite, or there is no universal limit speed, the same for all inertial observers (which possibility contradicts the principle of relativity). Thus the Ignatowski's result is latent in the seemingly innocent starting assumption $t' \neq t$. And what could be a more natural candidate for the universal limit speed in the world of phenomena than the speed of light?

Finally, a historical remark on the peculiar relationship between the principle of relativity and Maxwell's electromagnetic theory at the end of the nineteenth century. In their recent papers, Browne [7] and Moylan [5] discuss briefly the evolution of the principle of relativity, recalling contributions of the saints and martyrs of the philosophical calendar. Illustrating the crucial role played by Poincaré in the vigorous defense of the relativity principle, Moylan notes that "at the end of the nineteenth century, physics was in a terrible state of confusion. Maxwell's equations were not preserved under the Galilean transformation [...], the followers of Maxwell's electrodynamics were ready to uproot the relativity principle and reinstate a new form of geocentrism, where the relativity principle no longer held true." However, there is a little-known episode that testifies that the situation was more complex. A topic of discussion among physicists in the late nineteenth century was the electrodynamic interaction between a charge and a current–carrying loop at relative rest, that are moving uniformly with respect to the ether [43-45], cf also [46,47]. The basic feeling of the 'old' physicists was simple: it is highly improbable that anything depends on the motion with respect to the ether; physical effects depend only on the relative motion between ponderable bodies and on their mutual relative position. Since in the problem considered Maxwell's theory classically interpreted predicts a nonzero force [48], depending on unobservable speed v of the system with respect to the ether, Budde [43], FitzGerald [44] and Lorentz [45] postulated that charges were induced on the current loop in exactly that amount required to cancel the electrodynamic force due to the motion with respect to the ether. Their solution to the problem, reached through a rather contrived Budde's 'principle of neutralizing charge' (cf [46]), up to the second order terms in v/c coincides with what we think today to be the correct solution. Thus, some of the 'old' physicists were more ready to introduce an *ad hoc* hypothesis than to sacrifice the principle of relativity. Poincaré's melancholy phrase, "les hypothèses, c'est le fonds qui manque le moins,"†† expresses his longing for a principle, instead of piling up hypotheses. The longed-for principle, while counterintuitive and far from being clearly stated, was the second postulate.

†† Probably echoing the first two verses of the fable by Jean de La Fontaine, Le Laboureur et ses enfants: *Travaillez, prenez de la peine: C'est le fonds qui manque le moins.*

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